Analysis of the Lyman-alpha Forest in Cosmological Simulations Using Voigt-Profile Decomposition

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Abstract. We use an automated Voigt-profile fitting procedure to extract statistical properties of the Lyα forest in a numerical simulation of an $\Omega = 1$, cold dark matter (CDM) universe. Our analysis method is similar to that used in most observational studies of the forest, and we compare the simulations to recently published results derived from Keck HIRES spectra. With the Voigt-profile decomposition analysis, the simulation reproduces the large number of weak lines ($N_{\rm HI} \lesssim 10^{14} {\rm cm}^{-2}$) found in the HIRES spectra. At $z = 3$, the b-parameter distribution has a median of 35 km s^{-1} and a dispersion of 20 km s^{-1}, in reasonable agreement with the observed values. The comparison between our new analysis and recent data strengthens earlier claims that the Lyα forest arises naturally in hierarchical structure formation as photoionized gas falls into dark matter potential wells.

1.   Introduction

Absorption lines in quasar spectra, especially the "forest" of Lyα lines produced by concentrations of neutral hydrogen, are uniquely suited for probing structure formation in the high-redshift universe. Recent cosmological simulations that incorporate gas dynamics, radiative cooling, and photoionization reproduce many of the observed features of quasar absorption spectra, suggesting that the Lyα forest arises as a natural consequence of hierarchical structure formation in a universe with a photoionizing UV background (Cen et al. 1994; Zhang, Anninos, & Norman 1995; Hernquist et al. 1996, hereafter HKWM). Meanwhile, high-precision observations made using the HIRES spectrograph on the 10m Keck telescope have quantified the statistics of the low column density absorbers to unprecedented accuracy (e.g., Hu et al. 1995, hereafter HKCSR). Most of the lines found in HIRES spectra are weak absorbers with column densities $N_{\rm HI} < 10^{14} {\rm cm}^{-2}$. In order to compare to published line population statistics from HIRES data, it is essential to analyze the simulated spectra by Voigt-profile

decomposition. Here we compare simulated Lyα spectra from a simulation of the cold dark matter (CDM) scenario to HKCSR using an automated Voigt-profile fitting algorithm. The results presented here are a condensed version of those in Davé et al. (1996).

The physical model implicit in the decomposition technique is that of a collection of discrete, compact clouds, each characterized by a single velocity dispersion (thermal and/or turbulent). The simulations undermine this physical picture because the absorbing systems merge continuously into a smoothly fluctuating background, often contain gas at a range of temperatures, and are usually broadened in frequency space by coherent velocity flows that do not resemble Gaussian turbulence. Nonetheless, any spectrum can be described phenomenologically by a superposition of Voigt-profile lines, with the number of components increasing as the signal-to-noise ratio improves and more subtle features must be matched. The distributions of fitted column densities and b-parameters provide a useful statistical basis for comparing simulations and observations, and this is the approach that we adopt in these proceedings.

## 2.   Simulation and Artificial Spectra

The simulation analyzed here has the same initial conditions, cosmological parameters, and numerical parameters as that of HKWM (the reader is referred there for more details): a CDM universe with $\Omega = 1$, $H_0 = 50$ km s^{-1}Mpc^{-1}, baryon fraction $\Omega_b = 0.05$, $\sigma_8 = 0.7$, (roughly the value required to reproduce observed galaxy cluster masses; White, Efstathiou, & Frenk 1993), in a periodic simulation cube 22.222 comoving Mpc on a side. We generate artificial spectra at $z = 2$ and $z = 3$ along 300 random lines of sight through the simulation cube, using the methods described in HKWM and Cen et al. (1994).

Instead of the ν^{-1} UV background spectrum adopted by HKWM, we use the spectrum of Haardt & Madau (1996; hereafter HM), which is computed as a function of redshift based on the UV output of observed quasars and reprocessing by the observed Lyα forest. The mean opacity of the Lyα forest depends on the parameter combination Ω_b^2/Γ. Since observational determinations of Ω_b and Γ remain quite uncertain, we treat the overall intensity of the UV background as a free parameter and scale it to match the mean Lyα optical depth of Press, Rybicki, & Schneider (1993; hereafter PRS) of $\bar{\tau}_\alpha = 0.0037(1 + z)^{3.46}$. In order to do this at $z = 3$ with the original HM background intensity, we require $\Omega_b \approx 0.08$, in better agreement with Tytler, Fan, & Burles (1996). Once Ω_b^2/Γ is set, there is no further freedom to adjust the simulation predictions, and the remaining properties of the Lyα forest provide tests of the cosmological scenario.

3.   Fitting Voigt Profiles to Artificial Spectra

We want the analysis of our simulated spectra to closely match that used in typical observational studies, HKCSR in particular. To this end, we have developed an automated Voigt-profile fitting routine, AUTOVP, which allows us to efficiently handle large quantities of simulated data and which provides an objective algorithm that can be applied to real data. We first add noise ($S/N = 50$) to our simulated spectra. We then estimate the continuum in the simulated

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Figure 1.   LHS: Column density distributions $f(N_{\rm HI})$, the number of lines per unit redshift per linear interval of HI column density. Error bars denote 1σ Poisson counting errors. RHS: Distributions of b-parameters, for lines with $N_{\rm HI} > 10^{13}$ cm^{-2}.
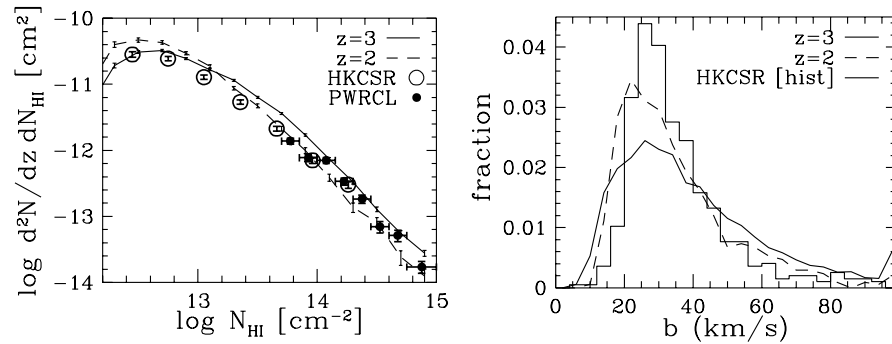
spectra, neglecting our *a priori* knowledge of it. Finally we apply AUTOVP to detect lines and fit Voigt profiles. In its first phase, AUTOVP identifies lines and makes an initial estimate of their column densities and b-parameters, and in its second phase, AUTOVP takes the initial guess and performs a simultaneous χ^2-minimization on the parameters $(v_{\rm central}, N_{\rm HI}, b)$ of all lines within each detection region. Three independent minimization techniques are employed in conjunction in order to reliably identify the global χ^2 minimum, and lines are added or removed based on formal significance criteria.

4.   Results

Figure 1 shows the column density distribution $f(N_{\rm HI})$, the number of lines per unit redshift per linear interval of $N_{\rm HI}$. Solid and dashed lines show the simulation results from AUTOVP at $z = 3$ and $z = 2$, respectively. Filled and open circles in Figure 1 show the observational results of PWRCL and HKCSR, respectively. We compute the HKCSR $f(N_{\rm HI})$ directly from their published line list, with no corrections for "incompleteness."

The mean redshift of the HKCSR lines is $\bar{z} = 2.9$, so the closest comparison is to the $z = 3$ simulation results. To make this comparison more exact, we convolved the $z = 3$ artificial spectra to a resolution $\Delta\lambda = 0.06$Å ($\Delta v = 3.7$ km s^{-1}) before applying AUTOVP. When analyzed by Voigt-profile decomposition, the simulation overproduces the number of lines by a factor of $1.5 - 2$ in the column density range 10^{13} cm$^{-2} \lesssim N_{\rm HI} \lesssim 10^{14}$ cm^{-2}. This excess of lines may therefore indicate a failure of the $\Omega = 1$, $\sigma_8 = 0.7$ CDM model. An alternative possibility, quite plausible at present, is that we have set the intensity of the UV background too low given our adopted value of Ω_b. If we adjust our intensity to force agreement with HKCSR's $f(N_{\rm HI})$ distribution, this lowers the mean optical depth to $\bar{\tau}_\alpha \approx 0.32$. This is well outside the 1σ range of PRS (figure 4), but is somewhat *above* the value $\bar{\tau}_\alpha(z = 3) \sim 0.25$ found by Zuo & Lu (1993). The uncertainty of our conclusions highlights the need for better observational determinations of $\bar{\tau}_\alpha(z)$; if $\bar{\tau}_\alpha$ is well known then the amplitude of $f(N_{\rm HI})$ becomes an independent test of the high-redshift structure predicted by a cosmological model.

Figure 1(b) shows the distribution of b-parameters for lines with $N_{\mathrm{HI}} \geq 10^{13}$ cm^{-2} from HKCSR (solid histogram) and from the AUTOVP analyses of the simulation at $z = 3$ and $z = 2$ (solid and dashed curves, respectively). We only use lines with $N_{\mathrm{HI}} \geq 10^{13}$ cm^{-2}, which eliminates lines whose identification and derived properties are sensitive to the value of S/N or to details of the fitting procedure. We find that distribution mean, median, and dispersion are 34.6, 39.3, and 20.8 km s^{-1}, respectively. From HKCSR line lists we obtain corresponding values of 31.4, 35.8, and 16.3 km s^{-1}; while systematically lower, the agreement is reasonable given that the analysis procedures are not identical in all their details. The most significant difference in the distributions is the presence of more narrow ($b < 20$ km s^{-1}) lines in the simulation than in the data. A possible explanation is that our equilibrium treatment of photoionization suppresses heating that can occur during rapid reionization (Miralda-Escudé & Rees 1994).

In summary, a Voigt-profile decomposition of simulated spectra in a CDM universe reproduces the column density and b-parameter distributions from Keck data reasonably well. Sharper tests of cosmological models against the statistics of the Lyα forest can be obtained by expanding the redshift range of comparisons, by improving the determination of $\bar{\tau}_\alpha(z)$, and by applying AUTOVP to observational data, so that the analyses of simulated and observed spectra are identical in detail. More interestingly, we are investigating different characterizations of line profiles which more accurately describe the physical state of the gas. While the spectra can always be fit within a discrete "cloud" model by postulating just the right clustering properties, the ubiquitous asymmetries and non-Gaussian features in the line profiles more likely signify the breakdown of the Voigt-profile paradigm itself, revealing the origin of the Lyα forest in the diffuse, undulating gas distribution of the high-redshift universe.

References

Cen, R., Miralda-Escudé, J., Ostriker, J.P., & Rauch M. 1994, ApJ, 427, L9

Davé, R., Hernquist, L.H., Katz, N. & Weinberg, D.H., 1996, ApJ, submitted

Haardt, F. & Madau, P. 1996, ApJ, 461, 20 (HM)

Hernquist, L.H., Katz, N., Weinberg, D.H., & Miralda-Escudé, J. 1996, ApJ, 457, L51 (HKWM)

Hu, E.M., Kim, T.S., Cowie, L.L., Songaila, A., & Rauch, M. 1995 AJ, 110, 1526 (HKCSR)

Miralda-Escudé, J. & Rees, M. 1994, MNRAS, 266, 343

Petitjean, P., Webb, J.K., Rauch, M., Carswell, R.F, & Lanzetta, K. 1993, MNRAS, 262, 499 (PWRCL)

Press, W.H., Rybicki, G.B., & Schneider, D.P. 1993, ApJ, 414, 64 (PRS)

Tytler, D., Fan, X.M., & Burles, S. 1996, Nature, 381, 207

White, S. D. M., Efstathiou, G., & Frenk, C. S. 1993, MNRAS, 262, 1023

Zhang, Y., Anninos, P., & Norman, M.L. 1995, ApJ, 453, L57

Zuo, L. & Lu, L. 1993, ApJ, 418, 601